Effects Of Cumulus Convection On Rapidly Intensifying Cyclones

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LONG-TERM GOAL

Our long term goal is to contribute to our understanding of the physics and dynamics of marine convection and mesoscale weather systems. Of particular interest are the processes in the development of cloud dropsize distribution, the structures and evolution of marine cyclones, tropical cloud clusters and hurricanes.

OBJECTIVES

Our objectives are

a) To describe the detailed structure of the air flow in a mature hurricane,
b) To understand the vertical force balance in the eye and the eyewall,
c) To investigate the presence of supergradient flow in hurricanes and the underlying processes,
d) To study the surface wind structures during landfall,
e) To investigate the transformation of a cold-core continental mesovortex into a warm-core tropical storm over the warm ocean,
f) To simulate the December 15 1992 cloud cluster during TOGA-COARE, and
g) To study whether inhomogeneous distribution of cloud droplets can lead to spatial variablity in supersaturation to acclerate the broadening of marine cloud dropsize spectra.

APPROACH

We used a numerical modeling approach. We carried out multi-scale simulations of Hurricane Andrew, a cloud cluster and a mesovortex. The simulations are first verified against observations to establish the validity of the simulations. The model results are then analysed to understand the various physical processes. For the study of the development of the cloud dropsize spectra, a direct numerical simulation (DNS) approach is used.

WORK COMPLETED

Using the modeling results from a high resolution multi-scale simulation of Hurricane Andrew, we completed an analysis of the air circulations during the mature stage of the storm and proposed a conceptual model of the air flow. Analysis of the vertical momentum and angular momentum budgets are accomplished to understand the vertical force balance in the eye and the eyewall and the

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supergradient flow in the hurricane. A study of the surface wind during landfall of the simulated Andrew was completed.

Simulation of the December 15, 1992 TOGA-COARE cloud cluster was successful. A simulation of a continental mesovortex and its transformation from a cold-core system to a warm-core tropical storm completed.

A review of the interaction of particles in a turbulent flow completed. A direct numerical simulation of the diffusional growth of cloud droplets in turbulence completed.

RESULTS

Liu et al. (1997) successfully simulated Hurricane Andrew using conventional observation as initial conditions. The high resolution dataset allowed us to answer a number of important questions regarding the inner-core structures of the storm.

We proposed a conceptual model of the axisymmetric structures of the air flow during the mature stage of Andrew(Liu et. al 1999). The model includes a main inflow (outflow) in the boundary layer (upper troposphere) with little radial flow in between, a divergent slantwise ascent in the eyewall, a penetrative dry downdraft at the inner edge of the eyewall, and a general weak subsiding motion in the eye above an inversion located near an altitude of about 2-3 km.

The penetrative dry downdraft originates from the return inflow in the upper troposphere and is driven by sublimative/evaporative cooling under the influence of the radial inflow of dry/cold air in the midtroposphere. It penetrates in a slantwise sense all the way to the bottom of the eye along the inner edge of the eyewall. The inversion divides the eye vertically into two parts, with a deep layer of warm/dry air above and a shallow pool of warm/moist air below. The air in the warm/moist pool originates from the main inflow and penetrative downdrafts. It is subject to the influence of the upward heat and moisture fluxes over the underlying warm ocean and plays an important role in supplying high-θe air for deep convective development in the eyewall. The air aloft descends at an average rate of 5 cm s^{-1} and has a residency time of several days.

We further showed that the flow fields are highly asymmetric. The storm-scale flow features a source-sink couplet in the boundary layer and dual-gyres aloft. The inner-core depicts alternate radial inflow and outflow and a series of inhomogeneous updrafts and downdrafts. Pronounced fluctuations of air motion are found in both the eye and the eyewall and a deep layer of upward motion sometimes appears at the center of the eye. The storm track indicates trochoidal oscillation. The main steering level is located in the midtroposphere (~4.5 km). The movement of the hurricane agrees well with the deep-layer mean winds.

We analyzed the vertical force balance in the inner-core region to gain insight into the processes leading to subsidence warming in the eye and the vertical lifting in the eyewall (Zhang et. al 1999b). We showed that the air in the eyewall, when averaged azimuthally, is stable for upright convection but unstable for slantwise ascent. However, the amount of positive buoyancy is small.

By partitioning the perturbation pressure forces into a buoyancy-induced component and a dynamically-induced component, we demonstrated that the buoyancy force generally offsets the buoyancy-induced

perturbation pressure force. However, the dynamically-induced perturbation pressure force is downward in the eye but upward in the outer portion of the eyewall. It plays an important role in maintaining the general descent in the eye and the lifting of high-θe air in the eyewall in the lower troposphere. We further showed that the dynamic force represents a response primarily to the radial shear of the tangential winds. We advanced a new theoretical explanation to describe the relationship among the subsidence warming in the eye, and the rotation and vertical shear in the eyewall.

We investigated the validity of gradient-wind balance in the eyewall through the analyses of radial momentum and absolute angular momentum (AAM) budgets during the deepening stage of the simulated Andrew (Zhang et. al 1999c). By performing temporal and azimuthal averaging, we showed the presence of supergradient flows from the bottom of the eye center to the upper outflow layer in the eyewall. The supergradient accelerations result mainly from the excess of the centrifugal force over the pressure gradient force, and they are on average twice as large as the local Coriolis force. The AAM budget calculations indicate that supergradient flows occur in the inflow region as a result of the inward AAM transport, and in the outflow region through the upward transport of AAM. The eyewall is dominated by radial outflow in which the upward transport of AAM overcompensates the spin-down effect of the outflow.

We analyzed the simulated surface winds during the landfall of Hurricane Andrew (Zhang et. al 1999a). We showed that for relatively weak flows, large discontinuity in surface winds exists across the coastline because of the change in surface roughness. For intense flows (> 50 m s^{-1}), the discontinuity is small because the tangential advection of momentum “smooths” out the wind discontinuity across the coastline. We further showed that the convergence induced by surface friction is maximized in the eyewall, rather than along the coastline during landfall. The simulated maximum surface wind decreased by more than 25% in two hours.

To explore the processes involved in the genesis of a tropical storm from a mesoscale convective system (MCS), we carried out a simulation of a continental cold-core mesovortex which dissipates and then regenerates over the warm Gulf Stream water into a warm-core tropical storm (Bao 1999). The results show that the mid-level mesovortex provides persistent convergence at its southern periphery for the continued convective development, whereas the convectively enhanced low-level flow increases surface energy fluxes over the warm water causing further conditional instability. Such feedback processes lead to the rapid deepening of the “tropical storm”. By decomposing the vertical relative vorticity associated with the tropical storm into the curvature vorticity and the shear vorticity, we showed that the amplification of a low-level vortex after 36 h is mainly contributed by the increase of curvature vorticity. We perform quasi-Lagrangian θ budget calculations which demonstrate that the descending motion in the center of the surface cyclone contributes to the formation of the warm core at 800 hPa.

We are investigating the organization of marine tropical convection in the December 15 1992 cloud cluster observed during TOGA-COARE. As a first step, we carried out a real data simulation of the case (Badrinath et. al 1999). Comparison with satellite and radar observations indicated that our simulation results are highly realistic, in terms of the spatial and temporal evolution of the onset of convection and the subsequent development. Other simulated features that are compared to observations are the vertical profiles of horizontal wind and the surface fluxes of sensible and latent heat. The model simulated wind directions closely match the observed directions from the wind

profiler, while the simulated wind speeds agree to within about 1-2 m s^{-1}. The simulated horizontal wind profiles over Kavieng, a station representative of the westerly wind burst regime, successfully captures the backing of winds with time above the 700 hPa level, indicating the slow westward migration of the trans-equatorial flow centered over the equator. In the presence of deep convection, the sensible and latent fluxes were enhanced. The maximum enhancement amounts to 2 times for latent heat fluxes and three times for sensible heat fluxes. The simulated dataset would be used to compute the heat and moisture budget of the cloud cluster.

To set the stage to study the rapid broadening of cloud droplet size spectra in maritime clouds, we reviewed recent progress on particle-turbulence interaction and its implications for cloud physics (Vaillancourt and Yau 1999). The subject is of considerable current interest as laboratory and numerical work, done mostly in mechanical engineering, showed that the velocity and the spatial distribution of particles may be modified significantly in a turbulent flow field. We present a review of this work and discuss the important non-dimensional parameters describing particle-turbulence interaction. We discuss also the pertinent scales for cloud droplets in clouds and compare with those explored in the mechanical engineering literature.

Motivated by recent observations in adiabatic cloud cores which show that the cloud droplet size distributions are broader than what is expected if all droplets were exposed to the same supersaturation, we investigate the hypothesis that non-uniformity in the spatial distribution of the size and position of droplets and/or variable vertical velocity in a turbulent medium may provide a source of variability in supersaturation (Vaillancourt et. al 1999). We used a direct numerical simulation approach which simulates the diffusional growth of thousands of droplets in a turbulent flow field. In Part I of this work, we presented results from simple experiments with no turbulent flow and with droplets randomly distributed in space.

We found that the random distribution of the position of droplets creates significant supersaturation perturbations. Whether these result in an increase in the width of the size distribution depends on the width of the initial size spectrum. When sedimentation is included, droplets grow in a variable environment. Sedimentation has the effect of reducing the decorrelation time of supersaturation perturbations to a few seconds, thereby decreasing the standard deviation of the distribution of the supersaturation perturbations by 35 to 50 % and the dispersion of the degree of growth (time integral of supersaturation) by ~ 65 %.

Comparison of our results with observations made in adiabatic cloud cores lead us to the conclusion that supersaturation perturbations caused by randomly distributed droplets produces too little broadening to explain the observations. The results of including a turbulent flow field will appear in a future paper in Part II.

IMPACT/APPLICATION

Our simulation of Hurricane Andrew represents one of the first successful high resolution multi-scale simulations of a mature hurricane. It shows the postential to use conventional observation data, together with a sophisticated numerical model and state-of-the-art physics package, to predict the intensity and track of a hurricane. Our direct numerical simulation of the growth of cloud droplets by

diffusion in a turbulent flow has not been attempted previously and should open the way for many fruitful investigations in cloud physics.

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